Measurement of Dijet Angular Distributions and Search for Quark Compositeness in pp Collisions at $\sqrt{s} = 7$ TeV

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Dijet angular distributions are measured over a wide range of dijet invariant masses in pp collisions at $\sqrt{s} = 7$ TeV, at the CERN LHC. The event sample, recorded with the CMS detector, corresponds to an integrated luminosity of 36 pb^{-1}. The data are found to be in good agreement with the predictions of perturbative QCD, and yield no evidence of quark compositeness. With a modified frequentist approach, a lower limit on the contact interaction scale for left-handed quarks of $\Lambda^+ = 5.6$ TeV ($\Lambda^- = 6.7$ TeV) for destructive (constructive) interference is obtained at the 95% confidence level.

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In the standard model, pointlike parton-parton scatterings in high energy proton-proton collisions can give rise to final states with energetic jets. At large momentum transfers, events with at least two energetic jets (dijets) may be used to confront the predictions of perturbative quantum chromodynamics (pQCD) and to search for signatures of new physics. In parton-parton scattering, the angular distribution of the outgoing partons, $d\hat{\sigma}/d\cos\theta^*$, is directly sensitive to the spin of the exchanged particle, where $\hat{\sigma}$ is the parton-level cross section and θ^* is the polar scattering angle in the parton-parton center-of-mass (c.m.) frame. While QCD predicts a noticeable deviation of the dijet angular distribution from Rutherford scattering, at small c.m. scattering angles the angular distribution is proportional to the Rutherford cross section, $d\hat{\sigma}/d\cos\theta^* \sim 1/(1-\cos\theta^*)^2$, characteristic of spin-1 particle exchange. The dijet angular distributions do not strongly depend on the details of the parton distribution functions (PDFs), since the angular distributions for the underlying processes, $qg \to qg$, $qq' \to qq'$, and $gg \to gg$, are similar.

For the scattering of massless partons, which are assumed to be collinear with the beam protons, the longitudinal boost of the parton-parton c.m. frame with respect to the proton-proton c.m. frame, y_{boost}, and θ^* are obtained from the rapidities y_1 and y_2 of the jets from the two scattered partons by $y_{\mathrm{boost}} = \frac{1}{2}(y_1 + y_2)$ and $|\cos\theta^*| = \tanh y^*$, where $y^* = \frac{1}{2}|y_1 - y_2|$ and where $\pm y^*$ are the rapidities of the two jets in the parton-parton c.m. frame. The rapidity is related to the jet energy E and the projection of the jet momentum on the beam axis p_z by $y = \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$. The variable $\chi_{\mathrm{dijet}} = \exp(2y^*)$ is used to measure the dijet angular distribution, which for collinear massless-parton scattering takes the form $\chi_{\mathrm{dijet}} = (1+|\cos\theta^*|)/(1-|\cos\theta^*|)$. This choice of χ_{dijet}, rather than θ^*, is motivated by the fact that $d\sigma_{\mathrm{dijet}}/d\chi_{\mathrm{dijet}}$ is flat for Rutherford scattering. It also allows signatures of new physics that might have a more isotropic angular distribution than QCD (e.g., quark compositeness) to be more easily examined as they would produce an excess at low values of χ_{dijet}. The quantity studied in this analysis is $(1/\sigma_{\mathrm{dijet}})(d\sigma_{\mathrm{dijet}}/d\chi_{\mathrm{dijet}})$, for several ranges of the dijet invariant mass M_{jj}. Previous searches for quark compositeness using the dijet angular distribution or related observables in pp and $p\bar{p}$ collisions have been reported at the $Sp\bar{p}S$ by the UA1 Collaboration [1], at the Fermilab Tevatron Collider by the D0 [2,3] and CDF Collaborations [4], and at the Large Hadron Collider (LHC) by the ATLAS Collaboration [5]. The CMS Collaboration has also published a search on quark compositeness with a smaller data sample using the dijet centrality ratio [6]. In this Letter, we present the first measurement of dijet angular distributions from CMS in pp collisions at $\sqrt{s} = 7$ TeV.

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Within the field volume are the silicon pixel and silicon strip tracker, the electromagnetic calorimeter (ECAL) and the hadron calorimeter (HCAL). The ECAL is made up of lead-tungstate crystals, while the HCAL is made of layers of plates of brass and plastic scintillator. These calorimeters provide coverage in pseudorapidity up to $|\eta| \leq 3$, where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle relative to the counterclockwise proton beam direction. An iron or quartz-fiber Čerenkov hadron calorimeter (HF) covers pseudorapidities $3 < |\eta| < 5$. In addition, a preshower detector made of silicon sensor planes and lead absorbers is located in front of the ECAL at $1.653 < |\eta| < 2.6$. The calorimeter cells are grouped in projective towers of granularity in pseudorapidity and azimuthal angle of 0.087×0.087 at central

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pseudorapidities, with coarser granularity at forward pseudorapidities. Muons are measured in gas-ionization detectors embedded in the steel magnetic field return yoke. A detailed description of the CMS detector can be found elsewhere [7].

Events were collected online with a two-tiered trigger system: level-1 (L1) and the high level trigger (HLT). For this study, events were selected with five inclusive single-jet triggers, with the following jet transverse momentum p_T thresholds at L1 (HLT): 20 GeV (30 GeV), 30 GeV (50 GeV), 40 GeV (70 GeV), 60 GeV (100 GeV), and 60 GeV (140 GeV). The jets at L1 and HLT were reconstructed using energies measured by the ECAL, HCAL, and HF, and were not corrected for the jet energy response of the calorimeters. All except the highest-threshold jet trigger were prescaled as the LHC instantaneous luminosity increased during the course of data taking. In each case, the trigger efficiency was measured as a function of dijet invariant mass M_{jj} using events selected by a lower-threshold trigger. For the analysis, M_{jj} and χ_{dijet} regions were chosen such that the trigger efficiencies exceeded 99%.

Jets were reconstructed offline from energies measured in the calorimeter towers using the anti-k_T clustering algorithm [8] with a distance parameter $R = 0.5$. Spurious jets from noise and noncollision backgrounds were eliminated by loose quality criteria on the jet properties [9]. The jet four-momenta were corrected for the nonlinear response of the calorimeters [10]. The performance of the CMS detector with respect to jet reconstruction is described in detail elsewhere [11].

Events were required to have a primary vertex reconstructed within 24 cm of the detector center along the beam line [12]. Events having at least two jets were selected and the two highest-p_T jets were used to measure the dijet angular distributions for different ranges in M_{jj}. We required $\chi_{\text{dijet}} < 16$ and $|y_{\text{boost}}| < 1.11$, thus restricting the rapidities y_1 and y_2 of the two highest-p_T jets to be less than 2.5. Nine analysis ranges were defined with the boundaries $0.25 < M_{jj} < 0.35$ TeV, $0.35 < M_{jj} < 0.5$ TeV, $0.5 < M_{jj} < 0.65$ TeV, $0.65 < M_{jj} < 0.85$ TeV, $0.85 < M_{jj} < 1.1$ TeV, $1.1 < M_{jj} < 1.4$ TeV, $1.4 < M_{jj} < 1.8$ TeV, $1.8 < M_{jj} < 2.2$ TeV, and $M_{jj} > 2.2$ TeV. The data correspond to integrated luminosities of 0.4, 3.5, 9.2, and 19.8 pb^{-1} for the lowest four M_{jj} ranges and 36 pb^{-1} for the remaining ones. The uncertainty on the integrated luminosity has been estimated to be 11% [13].

The dijet angular distributions are corrected for migration effects in χ_{dijet} and M_{jj} due to the finite jet energy and position resolutions of the detector. The correction factors were determined using two independent Monte Carlo (MC) samples: PYTHIA 6.422 [14] with tune D6T [15] and HERWIG++ 2.4.2 [16]. The four-momentum, rapidity, and azimuthal angle of each generated jet were smeared to reproduce the measured resolutions. The ratio of the two dijet angular distributions (the generated distribution and the smeared one) determined the unfolding correction factors for a given MC sample and for each M_{jj} range. The average of the correction factors for each M_{jj} range from the two MC samples formed the final unfolding correction applied to the data. The correction factors change the normalized dijet angular distributions for all M_{jj} ranges by less than 3%. For each M_{jj} range, the systematic uncertainty associated with each correction factor was set at 50% of its value. This approach covers the variations of the unfolding correction factors determined from HERWIG++ and different PYTHIA tunes (D6T and Z2 [17]) that vary on their modeling of the jet kinematic distributions. The use of a parametrized model to simulate the finite jet p_T and position resolutions of the detector, to determine the unfolding correction factors, resulted in a systematic uncertainty. This was estimated to be less than 1% for all M_{jj} ranges and was added in quadrature to the unfolding uncertainties.

The normalized dijet angular distributions are relatively insensitive to many systematic effects; in particular, they show little dependence on the overall jet energy scale. However, since χ_{dijet} depends on y^*, they are sensitive to the rapidity dependence of the jet energy calibration. Typical values for the jet energy scale uncertainties for the considered phase space in the variables of jet p_T and η covered in this analysis are between 3% and 4% [10]. The uncertainty on the χ_{dijet} distributions due to the jet energy calibration uncertainties was found to be less than 2.5%. The uncertainty on the dijet angular distributions from the jet p_T resolution uncertainty, estimated to be 10% [11], was found to be less than 1%. The total systematic uncertainty on the χ_{dijet} distributions, calculated as the quadratic sum of the contributions due to the uncertainties in the jet energy calibration, the jet p_T resolution, and the unfolding correction, is less than 3% for all M_{jj} ranges.

The corrected differential dijet angular distributions for different M_{jj} ranges, normalized to their respective integrals, are shown in Fig. 1. The data are compared to pQCD predictions at next-to-leading order (NLO) calculated with NLOJET++ [18] in the FASTNLO [19] framework. The calculations were performed with the CTEQ6.6 PDFs [20]. The factorization (μ_f) and renormalization (μ_r) scales were set to $\langle p_T \rangle$, the average dijet p_T. Nonperturbative corrections due to hadronization and multiple parton interactions, determined using the average correction from PYTHIA (D6T tune) and HERWIG++, were applied to the prediction. The uncertainties on the pQCD predictions, indicated by the shaded band in Fig. 1, are less than 6% (9%) at low (high) M_{jj}. These uncertainties include contributions due to scale variations and PDF uncertainties, as well as the uncertainties from the nonperturbative corrections. The uncertainty due to the choice of μ_f and μ_r scales was evaluated by varying the default

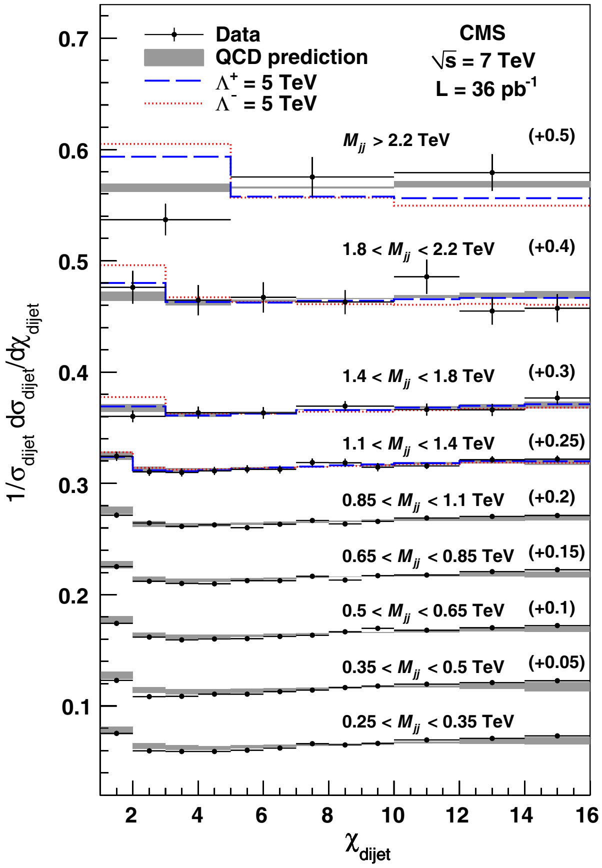

FIG. 1 (color online). Normalized dijet angular distributions in several M_{jj} ranges, shifted vertically by the additive amounts given in parentheses in the figure for clarity. The data points include statistical and systematic uncertainties. The results are compared with the predictions of pQCD at NLO (shaded band) and with the predictions including a contact interaction term of compositeness scale $\Lambda^+ = 5$ TeV (dashed histogram) and $\Lambda^- = 5$ TeV (dotted histogram). The shaded band shows the effect on the NLO pQCD predictions due to μ_r and μ_f scale variations and PDF uncertainties, as well as the uncertainties from the nonperturbative corrections added in quadrature.

choice of scales in the following six combinations: $(\mu_f, \mu_r) = (\langle p_T \rangle/2, \langle p_T \rangle/2)$, $(\langle p_T \rangle/2, \langle p_T \rangle)$, $(\langle p_T \rangle, \langle p_T \rangle/2)$, $(2\langle p_T \rangle, 2\langle p_T \rangle)$, $(2\langle p_T \rangle, \langle p_T \rangle)$, and $(\langle p_T \rangle, 2\langle p_T \rangle)$. These scale variations modify the predictions of the normalized χ_{dijet} distributions by less than 5% (9%) at low (high) M_{jj}. The uncertainty due to the choice of PDFs was determined from the 22 CTEQ6.6 uncertainty eigenvectors using the procedure described in Ref. [20], and was found to be less than 0.5% for all M_{jj} ranges. Half of the difference between the nonperturbative corrections from PYTHIA and HERWIG++ was taken as the systematic uncertainty, and was found to be less than 4% (0.1%) at low (high) M_{jj}. Overall there is good agreement between the measured dijet angular distributions and the theoretical predictions for all M_{jj} ranges.

The measured dijet angular distributions can be used to set limits on quark compositeness represented by a four-fermion contact interaction term in addition to the QCD Lagrangian. The value of the mass scale Λ characterizes the strengths of the quark substructure binding interactions and the physical size of the composite states. A color- and isospin-singlet contact interaction (CI) of left-handed quarks gives rise to an effective Lagrangian term: $\mathcal{L}_{qq} = \eta_0(2\pi/\Lambda^2)(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$ [21,22], where $\eta_0 = +1$ corresponds to destructive interference between the QCD and the new physics term, and $\eta_0 = -1$ to constructive interference. We investigate a model in which all quarks are considered composite as implemented in the PYTHIA event generator.

The contributions of the CI term in PYTHIA are calculated to leading order (LO), whereas the QCD predictions for the dijet angular distributions are known up to NLO. In order to account for this difference in the QCD plus CI prediction, the cross-section difference $\sigma_{\text{NLO}}^{\text{QCD}} - \sigma_{\text{LO}}^{\text{QCD}}$ was added to the LO QCD+CI prediction in each M_{jj} and χ_{dijet} bin. With this procedure, we obtain a QCD+CI prediction where the QCD terms are corrected to NLO while the CI terms are calculated at LO. Nonperturbative corrections due to hadronization and multiple parton interactions were also applied to the prediction. The prediction for QCD+CI at the scale of $\Lambda^+ = 5$ TeV ($\eta_0 = +1$) and $\Lambda^- = 5$ TeV ($\eta_0 = -1$) are shown in Fig. 1, for the four highest M_{jj} ranges.

We perform a statistical test discriminating between the QCD-only hypothesis and the QCD+CI hypothesis as a function of the scale Λ based on the log-likelihood-ratio $Q = -2\ln(\frac{L_{\text{QCD+CI}}}{L_{\text{QCD}}})$. The likelihood functions $L_{\text{QCD+CI}}$ and L_{QCD} are modeled as a product of Poisson likelihood functions for each bin in χ_{dijet} and M_{jj} in the four highest M_{jj} ranges. The prediction for each M_{jj} range is normalized to the number of data events in that range. The p values, $P_{\text{QCD+CI}}(Q \geq Q_{\text{obs}})$ and $P_{\text{QCD}}(Q \leq Q_{\text{obs}})$, are obtained from ensembles of pseudoexperiments. A modified frequentist approach [23–25] based on the quantity

$$\text{CL}_s = \frac{P_{\text{QCD+CI}}(Q \geq Q_{\text{obs}})}{1 - P_{\text{QCD}}(Q \leq Q_{\text{obs}})}$$

is used to set limits on Λ. This approach is more conservative than a pure frequentist approach (Neyman construction) and prevents an exclusion claim when the data may have little sensitivity to new physics [26]. Systematic uncertainties were introduced via Bayesian integration [27] by varying them as nuisance parameters in the ensembles of pseudoexperiments according to a Gaussian distribution convoluted with the shape variation induced to the χ_{dijet} distributions. We consider the QCD+CI model to be excluded at the 95% confidence level if $\text{CL}_s < 0.05$. Figure 2 shows the observed and expected CL_s as a function of the

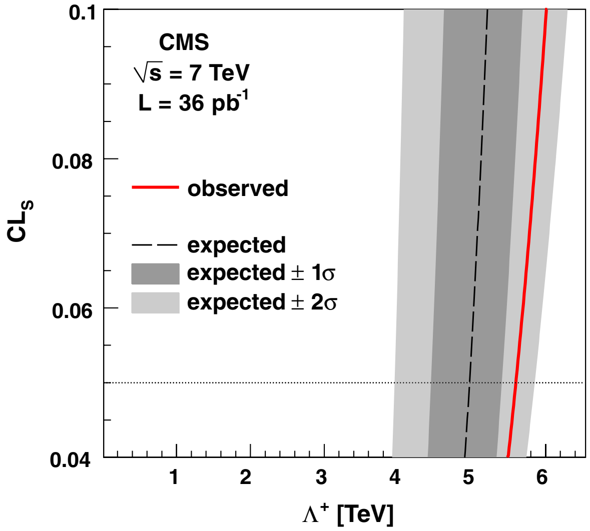

FIG. 2 (color online). Observed CL_s (solid line) and expected CL_s (dashed line) with one (two) standard deviation(s) indicated by the dark (light) band as a function of the contact interaction scale Λ^+. The 95% confidence level limits on Λ^+ are extracted from the intersections of the observed and expected CL_s lines with the horizontal line at $CL_s = 0.05$.

CI scale Λ^+. From this we determine the lower limit on Λ^+ to be 5.6 TeV. The observed limit agrees within 1.4 standard deviations with the expected limit of 5.0 TeV, which was evaluated at the median of the test statistics distribution of the QCD model. The observed limit is slightly higher than the expected one because, for the range $M_{jj} > 2.2$ TeV, the measured dijet angular distribution at low χ_{dijet} is lower than, although statistically compatible with, the QCD prediction. The limit for the CI scale was also extracted using an alternate procedure in which the data were not corrected for detector effects and instead the MC predictions were resolution smeared. The limit obtained was found to agree with the quoted one within 0.4%. The corresponding observed and expected limits on Λ^- are 6.7 and 5.8 TeV, respectively.

Shortly before the completion of this Letter, an exact NLO calculation of QCD effects to quark compositeness became available [28]. This calculation indicates that the limit on Λ^+ obtained in the present analysis, which only takes into account the LO prediction for the contribution of the contact interaction, might be overestimated by up to 10% compared to the value obtained if the NLO calculation were used.

In summary, CMS has measured the dijet angular distributions over a wide range of dijet invariant masses. The χ_{dijet} distributions are found to be in good agreement with NLO pQCD predictions, and are used to exclude a range of a color- and isospin-singlet contact interaction scale Λ for a left-handed quark compositeness model. With a modified frequentist approach, a lower limit on the contact interaction scale of $\Lambda^+ = 5.6$ TeV ($\Lambda^- = 6.7$ TeV) for destructive (constructive) interference at the 95% confidence level is obtained, which may be compared with a limit of 5.0 TeV (5.8 TeV) expected for the number of events recorded. These are the most stringent limits on the contact interaction scale of left-handed quarks to date.

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